Production-based emissions, consumption-based emissions and consumption-based health impacts of PM. carbonaceous aerosols in Asia

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Title: Production-based emissions, consumption-based emissions and consumption-based health impacts of $PM_{2.5}$ carbonaceous aerosols in Asia

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HIGHLIGHTS

- Total production-based emissions of BC & OC in 9 Asian regions were 5990 Gg-C.
- China accounted for 75% of production-based total emissions of BC & OC.
- Consumption-based health impact of BC & OC was presented by using Asian I-O tables.
- China accounted for 87% of consumption-based total health impacts of BC & OC.
- Characteristics of the consumption-based health impacts varied greatly by region.

Abstract

This study determined the production-based emissions, the consumption-based emissions, and the consumption-based health impact of primary carbonaceous aerosols (black carbon: BC, organic carbon: OC) in nine countries and regions in Asia (Indonesia, Malaysia, the Philippines, Singapore, Thailand, China, Taiwan, South Korea, and Japan) in 2008. For the production-based emissions, sectoral emissions inventory of BC and OC for the year of 2008 based on the Asian international input-output tables (AIIOT) was compiled including direct emissions from households. Then, a multiregional environmental input-output analysis with the 2008 AIIOT which was originally developed by updating the table of 2000 was applied for calculating the consumption-based emissions for each country and region. For the production-based emissions, China had the highest BC and OC emissions of 4520 Gg-C in total, which accounted for 75% of the total emissions in the nine countries and regions. For consumption-based emissions, China was estimated to have had a total of 4849 Gg-C of BC and OC emissions, which accounted for 77% of the total emissions in the Asia studied. We also quantified how much countries and regions induced emissions in other countries and regions. Furthermore, taking account of the source-receptor relationships of BC and OC among the countries and regions, we converted their consumption-based emissions into the consumption-based health impact of each country and region. China showed the highest consumption-based health impact of BC and OC totaling 111×10^3 premature deaths, followed by Indonesia, Japan, Thailand and South Korea. China accounted for 87% of the sum total of the consumption-based health impacts of the countries/regions, indicating that China's contribution to consumption-based health impact in Asia was greater than its consumption-based emissions. By elucidating the health impacts that each country and region had on other countries and from which country the impacts were received, we demonstrated that the characteristics of the consumption-based health impact varied significantly by country and region. We also determined the difference in the health impacts to other countries and regions due to the domestic final demand of each country and region, and the health impact due to the domestic final demand of that country or region.

Keywords

premature deaths, organic carbon, black carbon, consumption-based accounting, multiregional input-output analysis, source-receptor relationship

1. Introduction

The value of global trade is steadily increasing today with the globalization of commodity supply chains. Particularly in Asia with China leading the way, numerous commodities are manufactured in large quantities to support supply chains, with the region acting as a world factory that supplies countries around the globe. Asia's economic growth is sustained through massive consumption of fossil fuels, which of course is a critical source of emissions for many air pollutants. This implies that the generation of air pollutants in Asia is strongly related to the generating country's own exports and imports, that is, to its international trade.

There is currently demand to generally quantify the domestic and foreign environmental impacts of a country's consumption through analysis that incorporates the perspective of economic demand from international trade, in addition to accounting of only domestically generated environmental impacts such as greenhouse gases and air pollutants generated within a country. The latter, which is an inventory of environmental impacts, is said to be "production-based", in contrast with the former quantities, which are said to be "consumption-based" (Peters, 2008). In addition to production-based inventory, it is becoming critical to discuss the responsibilities for environmental management that a country should fulfill internationally, taking into account the consumption-based inventory (Munksgaard and Pedersen, 2001; Lenzen, 2007, 2008). Analysis of the environmental impact inventory from a consumption-based viewpoint is implemented using a multiregional input-output model (MRIO), with such analysis being widely implemented for climate change (Hertwich and Peters, 2009; Davis and Caldeira, 2010; Skelton *et al.*, 2011; Nansai *et al.*, 2012a), air pollution (Hertwich, 2011; Nansai *et al.*, 2012b), water consumption (Daniels *et al.*, 2011), endangered species (Lenzen et al., 2012), and land use (Steen-Olsen et al., 2012; Weinzettel et al., 2013).

However, in applying a consumption-based approach to diverse environmental impacts as mentioned above, we must remember that trans-boundary pollution of air pollutants exists as pointed out by Lin *et al.* (2014). If the purpose of reducing air pollutants is to reduce health damages from exposure to air pollutants, then it is necessary to determine the extent of health impacts that are ultimately caused by consumption-based emissions, taking into account the atmospheric transport of air pollutants. This means that it is essential to design an international framework for atmospheric environmental management that takes into account the inventory of consumption-based health impact.

This study focuses on primary carbonaceous particles of black carbon (BC) and organic carbon (OC), which are major components of $PM_{2.5}$ (particulate matter that is 2.5 μm or less in aerodynamic diameter) among air pollutants. We prepared three inventories covering nine countries and regions in Asia (Indonesia, Malaysia, the Philippines, Singapore, Thailand, China, Taiwan, South Korea, and Japan) for the purpose of determining their structural characteristics. The three inventories that we prepared were those of the production-based emissions, the consumption-based emissions, and the consumption-based health impact.

2. Materials and method

2.1 Accounting framework of production-based emissions, consumption-based emissions, and consumption-based health impact of black carbon (BC) and organic carbon (OC)

Here we will explain the concepts of the two emissions (production-based and consumption-based) and the consumption-based health impact that we estimated in this study. Figure 1 shows the different patterns of the three inventories of country A. The production-based emissions (1) are the quantity of BC and OC emitted domestically in country A. Direct emissions from country A can be categorized into **E1** emitted in order to satisfy the export demand of country A, and **E2** emitted in order to satisfy the domestic final demand. **E2** includes BC and OC directly emitted from households. The production-based emissions are the sum of **E1** and **E2** (**E1**+**E2**).

The consumption-based emissions of country A (2) are emissions caused by the domestic final demand of country A. Accordingly, in addition to **E2**, it includes BC and OC emitted in the process of producing commodities abroad and which are imported in order to satisfy domestic final demand of country A. If country A imports commodities from country C, then the domestic final demand of country A induces emissions **E3** in country C, which together with **E2** (**E2**+**E3**) constitutes the consumption-based emissions of country A.

The consumption-based health impact of country A (3) indicates the human health impacts from BC and OC generated in and outside of the country (in country A and in country C) by the domestic final demand of country A. If BC and OC emitted in country C (**E3**) is transported atmospherically to country B by meteorological conditions, health impacts arise in country B. These health impacts are labeled **H3**. Additionally, BC and OC emitted in country A (**E2**) give rise to health impacts in country A, the quantity of which is labeled **H2**. Health impacts **H2** and **H3** are health impacts generated by the final domestic demand of country A, defined as the sum of the consumption-based health impacts of country A (**H2**+**H3**).

In this paper, the country that induces emissions from its domestic final demand is categorized as the "driver country", the country that actually emits BC and OC due to that domestic final demand is the "source country", and the country that receives health impacts from BC and OC emitted from the source country is the "receptor country".

2.2 Production-based emissions of BC and OC

To begin with, this study compiled a sectoral emission inventory of primary carbonaceous aerosols (BC and OC) in Asian regions based on the sector classification in the Asian international input–output tables (AIIOT) published by IDE-JETRO (2006). The Asian regions included are Indonesia, Malaysia, the Philippines, Singapore, Thailand, China, Taiwan, South Korea, and Japan, and the target year for the inventory is 2008. However, the latest publically available AIIOT is for the year of 2000, and we therefore originally estimated AIIOT for the year of 2008 by updating the 2000 AIIOT with the trade-RAS method (Mori and Sasaki, 2007). The "RAS" method (Stone and Brown, 1962) is the most widely used method for estimating input coefficient matrix in updating input–output table, based on the input-output structure of an older survey-based table and information on the margins (such as total intermediate input use and total intermediate inputs supplied by industry) for the object table. The trade-RAS method improves the predictive accuracy of the conventional RAS method by incorporating updated information on multilateral trade (trade value between countries). We utilized UN COMTRADE (United Nations Statistics Division, 2010) for multilateral trade data to compile the 2008 AIIOT that comprises 76 intermediate sectors and a final demand sector including household consumption in the nine countries and regions.

We considered fossil fuel combustion and agricultural open burning of residues of rice, sugar cane, rape seeds, roots, tubers, corn, wheat, and cotton as emission sources of

BC and OC, and estimated emissions associated with fossil fuels combustion in sector j (j=1...76) in region r (r = 1...9) and emissions from agricultural open burning of the sector j in region r, BC_j^r [Gg-C] and OC_j^r [Gg-C]. BC and OC directly emitted from households in region r, BC_h^r [Gg-C] and OC_h^r [Gg-C], are also calculated.

Estimation for BC_j^r and OC_j^r employed various available statistics; for instance, the production of crops referred to Food and Agricultural Commodities Production (FAO, 2011), China Statistical Yearbook 2006 (National Bureau of Statistics of China, 2006), China Statistical Yearbook 2009 (National Bureau of Statistics of China, 2009), and Taiwan Input-Output Table (Directorate General of Budget, Accounting and Statistics, Executive Yuan, 2011). The ratios for open burning in combination with emissions factors by crop types (Streets et al., 2004) were obtained from Cao et al., 2008 (rice), and Zhang et al., 2008 (wheat and corn). The amounts of fossil-fuel-derived carbonaceous aerosol were determined with emissions factors by fuel types used in REAS (Ohara et al., 2007) and energy consumptions reported in the International Energy Agency (IEA) energy balance sheet (IEA, 2011a, 2011b). In terms of BC and OC from agricultural open burning of residues in Japan, we used the National GHGs Inventory Report of Japan (NIES, 2010) for the amount of rice straw and rice husk, and the emission factor for agricultural burning (Cao et al., 2006), and estimated the amounts of other crops based on statistics on methane emissions from agricultural open burning of crop residues (NIES, 2010).

By summing sectoral emissions over sectors j and including household emissions as in Eq. (1), the total emissions of BC and OC generated in region r=r*, PE^{r*} [Gg-C], were calculated. Herein, we refer to this emission as the production-based emission in region r*.

$$PE^{r*} = \sum_{j=1}^{76} BC_j^{r*} + BC_h^{r*} + \sum_{j=1}^{76} OC_j^{r*} + OC_h^{r*} \tag{1}$$

2.3 Consumption-based emissions of BC and OC with a multiregional input-output model (MRIO)

The international induced emissions associated with the final demands of region *r** were quantified by an environmental multiregional input-output analysis with the 2008 AIIOT as follows. First, unit direct emissions for sector *i* (*i*=1...76) in region *r*, d_i^r [Gg-C/1000 USD], were prepared by Eq. (2). In this equation, X_i^r is the total output of sector *i* in region *r* and values are based on the 2008 AIIOT.

$$d_i^r = \frac{BC_i^r + OC_i^r}{X_i^r} \tag{2}$$

Then, we defined unit direct emission vector $\mathbf{d}[1\times ri] = \left(d_i^r\right)$, where d_i^r are vector elements, and the final demand vector of region *r**, $\mathbf{f}^{r*}[si\times 1] = \left(f_i^{sr*}\right)$, composed of f_i^{sr*} [1000 USD], which represents the final demand from region *r** to sector *i* of region *s* (*s* = 1...9). Equation (3) determined the induced emission vector $\mathbf{e}^{r*}[si\times 1] = \left(e_i^{sr*}\right)$ whose elements are e_i^{sr*} [Gg-C] showing the emission from sector *i* in regions induced by the final demand of region *r**. The emission induced by final demand of region *r** among the nine regions, or the consumption-based emission of the region *r**, CE^{r*}, was calculated by Eq. (4) with inclusion of direct emissions from households in the region *r**.

$$\mathbf{e}^{r*} = \hat{\mathbf{d}}\left(\mathbf{I}-\mathbf{A}\right)^{-1}\mathbf{f}^{r*} \tag{3}$$

$$CE^{r*} = \sum_{s=1}^{9}\sum_{i=1}^{76} e_i^{sr*} + BC_h^{r*} + OC_h^{r*} \tag{4}$$

Here, $\mathbf{A}[si \times rj] = \left(a_{ij}^{sr}\right)$ is an input coefficient matrix of which an element a_{ij}^{sr} denotes the input from sector *i* in region *r* to unit production of sector *j* in region *r*. The input coefficient a_{ij}^{sr} was determined by x_{ij}^{sr} / X_j^r, of which the annual transaction between sector *i* in region *s* and sector *j* in region *r*, x_{ij}^{sr}, is taken from the 2008 AIIOT. $\mathbf{I}[si \times rj]$ is an identity matrix, and a vector with the symbol ^ means a matrix in which the diagonal elements are the elements of the vector and all other elements are zero.

2.4 Consumption-based health impact of BC and OC emissions considering their source-receptor relationship

Aerosol particles are transported in the atmosphere from its emission source to other locations, which means some of the BC and OC emitted in a region have an impact on people living in other regions. Taking account of this source-receptor relationship (SRR) between a region discharging BC and OC and a region as a recipient of those emissions, this study estimated the consumption-based impacts for each region by transforming the consumption-based emissions with the use of an SRR matrix. The prepared SRR matrix for the intermediate sectors, $\mathbf{Q}[si \times r] = \left(q_i^{sr}\right)$, is composed of elements q_i^{sr}, where q_i^{sr} represents the number of premature deaths in region *r* (receptor) caused by unit emission from sector *i* in region *s* (source). Similarly, the SRR matrix for households, $\mathbf{U}[s \times r] = \left(u_h^{sr}\right)$, was also complied, where u_h^{sr} is the number of premature deaths in region *r* (receptor) caused by unit emission from household (*h)* in region *s* (source).

We computed the values by applying the methodology in Nishizawa *et al.* (2012) for q_i^{sr} and u_h^{sr}. Specifically, numerical simulations were conducted using the Weather Research and Forecasting (WRF) modeling system (Skamarock *et al.*, 2008) and the

Community Multiscale Air Quality (CMAQ) modeling system (Byun and Schere, 2006) with Regional Emission inventory in ASia (REAS) (Ohara *et al.*, 2007) to determine SRR of the yearly averaged concentrations of BC and OC emitted from five sectors (power plant, industry, transport, agriculture, and residence) in East and Southeast Asia. In addition to the SRR analysis, the premature mortalities for five emission sectors were also estimated using the concentration-response function (Environmental Benefits Mapping and Analysis Program, 2012), population-weighted annual mean concentration, annual baseline mortality rate, and exposed population to evaluate the impact of BC and OC on human health in units of premature deaths.

Multiplication of the vector $\mathbf{e}^{r*}$ by the SRR matrix $\mathbf{Q}$ as Eq. (5) converts e_i^{sr*}, the emission from sector *i* in region*s* induced by the final demand of region *r**, into m_r^{r*}, the number of premature deaths in region *r* (receptor) caused by the emission, in the form of the vector $\mathbf{m}^{r*}\left[r \times 1\right] = \left(m_r^{r*}\right)$. In Eq. 5, the symbol (') denotes matrix transposition.

$$\mathbf{m}^{r*} = \mathbf{Q}'\mathbf{e}^{r*} \tag{5}$$

We also converted the emissions from households into the number of premature deaths due to their impact with u_h^{sr}. Then summing m_r^{r*} and the premature deaths of households for all regions *r* as Eq. (6) formulated the consumption-based impacts of region *r**, which implied the number of premature deaths in the nine Asian regions induced by the final demand of region *r** (driver).

$$CI^{r*} = \sum_{r=1}^{9} m_r^{r*} + \sum_{r=1}^{9} u_h^{r*,r}\left(BC_h^{r*} + OC_h^{r*}\right) \tag{6}$$

3. Results and discussion

3.1 Production-based emissions of BC and OC in the Asian region

Figure 2 shows the BC and OC emissions (production-based emissions) in 2008 from the nine countries and regions covered in this study. The source of emissions was separated into emissions from industrial sources and emissions from households. Emissions in the entire Asian region covered were 5990 Gg-C (gigagrams of carbon), with emissions from China the highest at 4520 Gg-C. Industrial emissions of BC from China were 489 Gg-C and household emissions of BC were 808 Gg-C, with the main source of industrial emissions from transportation (85 Gg-C), other grain (85 Gg-C), and iron and steel (49 Gg-C). Industrial emissions of OC were 563 Gg-C and household emissions of OC were 2660 Gg-C, so that household emissions of OC accounted for 59% of the total emissions for China. The main sources of industrial emissions were from paddy (234 Gg-C), other grain (101 Gg-C), and food crops (43 Gg-C).

Indonesia was the second-highest emitting country with total emissions of 807 Gg-C. Similar to China, household OC emissions were highest at 546 Gg-C, which accounted for 60% of total emissions. Industrial OC emissions were estimated at 108 Gg-C, and the main sources of emissions were from food crops (83 Gg-C), transportation (10 Gg-C), and paddy (9 Gg-C). Thailand was the third-highest emitting country with total emissions of 272 Gg-C, but the gap between Thailand and the two highest emitting countries was extremely large. Following Thailand were Japan (115 Gg-C) and the Philippines (113 Gg-C).

Focusing on the share of BC and OC emissions in each country/region, the countries/regions that like China and Indonesia had higher BC emissions than OC emissions were Malaysia, the Philippines, Thailand, and Taiwan. The main sources of OC emissions in these countries were food crops for industrial OC emissions and OC emissions from households, so that these countries and regions can be characterized as agricultural countries and countries with heavy household use of biomass fuels. By contrast, countries that had greater BC emissions were Japan, South Korea, and Singapore, reflecting the characteristics of industrial countries. The main source of industrial BC emissions for Japan were from transportation (12 Gg-C), electricity and gas (10 Gg-C), and wholesale and retail trade (5 Gg-C), for South Korea were from transportation (24 Gg-C), electricity and gas (2 Gg-C), and refined petroleum and its products (1 Gg-C), and for Singapore were from electricity and gas (2 Gg-C), refined petroleum and its products (1 Gg-C), and transportation (1 Gg-C). The common characteristic of these was the contribution from electricity and gas, and transportation.

3.2 Consumption-based emissions of BC and OC in the Asian region

Figure 3 shows the BC and OC emissions induced in Asian countries and regions by the domestic final demand of each country. These emissions are the quantity generated in the nine countries and regions covered in this study, out of the BC and OC consumption-based emissions of each country and region. In 2008, China showed the largest consumption-based emissions in Asia, with estimated BC emissions of 1516 Gg-C and OC emissions of 3333 Gg-C, totaling 4849 Gg-C. Of this amount, Figure 2 shows that 3468 Gg-C was directly emitted from households in China, with 1381 Gg-C in indirect emissions induced domestically and abroad by China’s domestic final demand. While OC emissions were a great deal higher, they were caused by OC emissions directly from households of 2660 Gg-C, with the dominant reason being the high consumption of biomass fuels such as wood in Chinese households. Indonesia, which had the second-highest consumption-based emissions, displayed the same characteristics as China.

Indonesia's emissions of 805 Gg-C were much smaller than China's, of which 666 Gg-C were emissions directly from households. For the composition of BC and OC emissions, OC emissions accounted for 652 Gg-C of the total 805 Gg-C emissions, of which household OC emissions accounted for 546 Gg-C.

By contrast, Japan and South Korea's combined BC and OC consumption-based emissions were 165 Gg-C and 66 Gg-C, respectively, of which just 5.8 Gg-C and 11.9 Gg-C, respectively, were directly from household consumption, with the majority of their consumption-based emissions comprising emissions induced by final demand. Japan's composition of BC and OC emissions was unlike that of China and Indonesia, with Japan having BC emissions of 85 Gg-C and OC emissions of 80 Gg-C, indicating higher BC emissions from fossil fuels. Similarly, South Korea had BC emissions of 34 Gg-C and OC emissions of 32 Gg-C, indicating that there were sharp differences in the chemical composition of carbonaceous aerosol, in addition to differences in the size of consumption-based emissions in the Asian region.

Figure 4 shows the percentage of emissions by region that were induced by the domestic final demand of each country or region, providing a breakdown of the countries and regions (drivers) and the regions in which their consumption-based emissions were actually emitted (sources). Besides Singapore, the highest percentage of emissions was direct emissions from domestic households and emissions that domestic industries were induced to generate. For China, Thailand, and Indonesia in particular, these accounted for almost 100% of emissions, and the three countries induced an extremely low percentage of BC and OC emissions in other countries.

China stood out in terms of being induced to generate emissions, with Singapore, Japan, and South Korea accounting for 23%, 17%, and 12% respectively of China's overall induced emissions, as these countries had a comparatively strong dependency on China for consumption-based emissions. Furthermore, certain countries and regions accounted for a high percentage of emissions induced in Thailand, that being Singapore at 13%, Taiwan at 11%, and Japan at 7% of Thailand's overall induced emissions. Singapore stood out in having accounted for a high percentage of emissions induced in Malaysia at 18% and in Indonesia at 12%. As an entrepôt trade country, Singapore's strong economic ties with these countries due to its economic structure and geographic proximity were reflected in the BC and OC inducement relationship.

3.3 Consumption-based health impact of BC and OC emissions in the Asian region

Figure 5 shows the health impact based on the consumption of each country and region, measured in units of 1000 deaths. Specifically, we calculated the human exposures to BC and OC from the consumption-based emissions shown in Figure 4, based on the SRR of BC and OC, and then calculated the size of the health impact from the exposures (premature deaths). The country with the highest consumption-based health impact was China, with an estimated BC impact of 46×10^3 deaths and OC impact of 66×10^3 deaths, totaling 111×10^3 deaths. Indonesia had the second-highest consumption-based health impact, totaling 10.3×10^3 deaths, followed by Japan with 2.69×10^3 deaths, Thailand with 1.69×10^3 deaths, and South Korea with 1.27×10^3 deaths, which rounded out the top five countries for consumption-based health impact. Each country displayed certain characteristics for BC and OC contribution. Like China, for Indonesia and Thailand, the OC impact was higher at 8.3×10^3 deaths and 1.2×10^3 deaths, respectively. The higher OC impact than BC impact was common to all countries and regions except Japan and South Korea. The BC impact for Japan and South Korea was 1.5×10^3 deaths and 0.71×10^3

deaths, respectively, exceeding the OC impact of 1.2×10^3 deaths and 0.56×10^3 deaths, respectively.

Figure 6 shows a breakdown of the consumption-based health impact in each country and region (drivers) as was shown in Figure 5, by the country and region receiving the health impact (receptors). Here, the health impact occurring in the driver country is displayed as the domestic percentage of consumption-based health impact. An obvious major characteristic is that the domestic percentage accounted for less than half of the overall impact for certain countries and regions. The country with the smallest domestic impact was Singapore, with only 7%, followed by Malaysia with 26% and Taiwan with 38%. In other countries, the domestic impact accounted for more than half of the overall impact, as was the case with China and Indonesia at 98% each. For the impact on other countries, countries that had an extremely high share of impact on China were Singapore at 59%, Malaysia at 46%, and Taiwan at 39%. Even Japan and South Korea, which had a high percentage of domestic impact, had shares of impact on China of 27% and 25%, respectively, boosted by the size of induced emissions from trade and their large populations. The Philippines had a higher share of impact on Indonesia than did China and had a more idiosyncratic structure than other countries and regions.

Figure 7 shows the countries and regions receiving health impacts and the countries or regions (drivers) whose domestic final demand generated these impacts. Using Japan as an example, if the health impact from BC and OC that Japan received due to the domestic final demand of the nine countries and regions covered is set at 100%, then 73% of the health impact was domestic, meaning that it was caused by Japan’s domestic final demand and direct emissions from Japanese households. The share of 21% represents the health impact from BC and OC that were generated in Japan or other countries due to

China's domestic final demand and transported in Japan. Singapore and Taiwan had high non-domestic percentages, with the health impact arising there mainly due to the domestic final demand of other countries. Forty-eight percent of Singapore's health impact was due to Indonesia's demand, and 60% of Taiwan's health impact was due to China's demand. Roughly half of Malaysia's and South Korea's health impacts originated from own domestic demand, but the main driver countries for Malaysia were Indonesia at 23% and the Philippines at 14%. Forty-five percent of South Korea's health impact was due to China's demand. For China and Indonesia, 99% and 98% of their health impacts, respectively, were due to domestic demand, quantifying that there are large characteristic differences between countries in the composition of health impacts received from the economic demand of countries.

Table 1 shows the difference between the health impact on other countries and regions (receptors) from the domestic final demand of each country and region (drivers), and the health impact due to that country or region's domestic final demand. A positive value means that the health impact on the receptor country due to the driver country's demand exceeded the health impact received by the driver country due to the receptor country's demand. For instance, Japan (driver) had a large health impact on China equivalent to 234 deaths, and received a large health impact from South Korea equivalent to 70 deaths. The positive sum value of 314 deaths indicates that the health impact triggered by Japan's domestic final demand was greater than the impact that Japan received from the demand of other countries. Conversely, South Korea had a negative sum value of −340 deaths, indicating that the health impact received was higher, mainly due to China's economic demand.

3.4 Comparison between production-based emissions, consumption-based emissions, and consumption-based health impact

Figure 8 shows the share (%) of each country and region's production-based emissions, consumption-based emissions, and consumption-based health impact, out of the totals for the Asian region that we calculated in this study. For example, China accounted for 75% of the production-based emissions in the Asian region covered in this study, but its share of the production-based health impact was even higher at 77%, with the share of consumption-based health impact at 87%. It is important to note this 12% difference between the share of consumption-based emissions and share of consumption-based health impact. This difference suggests that reducing China's consumption-based emissions is even more critical to reducing health impacts in Asia than is indicated by China's share of emissions in Asia. In all countries and regions besides China, the share of health impacts is lower than the share of consumption-based emissions, and so measures for consumption-based emissions are of lesser importance from the viewpoint of health impact.

Table 2 shows the ratio of consumption-based emissions to production-based emissions (Gg-C/Gg-C) and the ratio of consumption-based health impact to consumption-based emissions (deaths/Gg-C), giving their corresponding average values and coefficient of variation (%). A smaller coefficient of variation from the average implies that consumption-based emissions can be roughly calculated by multiplying the production-based emissions by the average value (1.01). However, the 19.7% coefficient of variation is significant and indicates that it is necessary to calculate the consumption-based emissions through estimation using MRIO, as we did in this study. Similarly, the average value for the ratio of consumption-based health impact to consumption-based emissions was 12.48, with an extremely high coefficient of variation of 45.1%. This confirms the importance of analysis by focusing on SSR, although it is not appropriate to theorize that a simple proportional relationship exists between the consumption-based emissions and the consumption-based health impact.

3.5 Ranges of the two emissions and impact considering uncertainties of emission factors

We quantified uncertainty of the production-based emissions, the consumption-based emissions, and the consumption-based impacts for each country/region considering on the variability of the emission factors of fossil fuel by Streets et al. (2003) and those of crop residues by Cao et al. (2006). Table 3 shows the ranges obtained for the production-based emissions, the consumption-based emissions, and the consumption-based health impact of each country or region that we derived in this study, by using the maximum and minimum values for the emission factors mentioned above. This means that it only reflects the uncertainty of production-based emissions and does not encompass uncertainty arising from the process of calculating the consumption-based emissions and health impacts. The range is generally between 50% and 150% for the countries and regions, which does not confirm that any country stands out with a high or low uncertainty.

4. Conclusions

This study covered nine countries and regions in Asia and estimated their BC and OC emissions in 2008. The emissions in the entire Asian region covered were estimated at 5990 Gg-C. China had the highest production-based emissions at 4520 Gg-C, which accounted for 75% of emissions in the Asian region, the main source of which was OC directly emitted from households. We then used MRIO to calculate BC and OC emissions induced (consumption-based emissions) in the Asian region covered, due to the domestic final demand of each country/region. China accounted for 77% of the total 4849 Gg-C of consumption-based emissions for the nine countries and regions. Additionally, we quantified the extent to which each country or region induced emissions in other countries and regions. We furthermore converted the consumption-based health impact from the consumption-based emissions, taking into account the SRR for BC and OC and the exposed population. China accounted for 87% of the sum total of the consumption-based health impact of the countries/regions. By elucidating the health impacts that each country/region had on other countries and from which country impacts were received, we showed that there were countries whose contribution was extremely high and other countries whose contribution was low, and also that the characteristics of the consumption-based health impact varied significantly by country and region. We estimated the range of the two emissions and the impact, taking into account the uncertainty of the emissions factors for BC and OC, and confirmed that the countries and regions generally had a range between 50% and 150% based on the estimated values in this study.

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Legends

Table 1: Difference between the health impact of BC and OC that a country/region's domestic final demand gives to other countries/regions and the health impact which the country/region received caused by the domestic final demand of other countries/regions

Table 2: Ratio of consumption-based emissions of BC and OC to production-based emissions, and ratio of consumption-based health impact to consumption-based emissions for each country and region

Table 3: Uncertainty ranges of the production-based emissions of BC and OC, the consumption-based emissions, and the consumption-based health impact for each country and region taking into consideration the variations of the BC and OC emission factors.

Figure 1: Concept of the three inventories on BC and OC emissions: the production-based emissions, the consumption-based emissions, and the consumption-based health impact

Figure 2: Production-based emissions of BC and OC for each country and region in Asia in 2008

Figure 3: Consumption-based emissions of BC and OC for each country and region in Asia in 2008

Figure 4: Regional composition of the consumption-based emissions of BC and OC for each country and region in Asia in 2008 from the viewpoint of which country's domestic final demand (driver) induced which country's emissions (source)

Figure 5: Consumption-based health impact of BC and OC for each country and region in Asia in 2008.

Figure 6: Regional composition of the consumption-based heath impact of BC and OC

for each country and region in Asia in 2008 from the viewpoint of which country's domestic final demand (driver) has a health impact on which country (receptor)

Figure 7: Regional composition of the consumption-based heath impact of BC and OC for each country and region in Asia in 2008 from the viewpoint of which country's health impact (receptor) is due to which country's domestic final demand (driver)

Figure 8: Comparison of the share of the production-based emissions of BC and OC, the consumption-based emissions, and the consumption-based health impact in Asia in 2008 to the total of the countries and regions studied.

Table 1

[Deaths/yr]

		The countries and regions causing the health impact of BC and OC by their domestic final demand (drivers)								
		Indonesia	Malaysia	The Philippines	Singapore	Thailand	China	Taiwan	South Korea	Japan
The countries and regions receiving health impact of BC and OC (receptors)	Indonesia	–	−24	67	−15	2	−18	8	8	65
	Malaysia	24	–	13	−2	−25	−130	−2	−5	5
	The Philippines	−67	−13	–	−3	12	28	1	3	11
	Singapore	15	2	3	–	−10	−68	0	−4	−3
	Thailand	−2	25	−12	10	–	160	−7	8	73
	China	18	130	−28	68	−160	–	−92	−418	234
	Taiwan	−8	2	−1	0	7	92	–	−2	0
	South Korea	−8	5	−3	4	−8	418	2	–	−70
	Japan	−65	−5	−11	3	−73	−234	0	70	–
	Sum	−92	121	28	65	−254	249	−91	−340	314

Table 2

	Consumption–based emissions/ Production–based emissions [Gt–C/Gt–C]	Consumption–based health impact/ Consumption–based emissions [Deaths/Gt–C]
Indonesia	1.00	12.8
Malaysia	0.82	6.0
The Philippines	0.83	6.1
Singapore	1.24	11.2
Thailand	0.88	7.2
China	1.07	23.0
Taiwan	0.89	10.5
South Korea	0.90	19.2
Japan	1.45	16.2
Average[–]	1.01	12.48
Coefficient of variation [%]	19.7	45.1

Table 3

	Production–based emissions	Consumption–based emissions	Consumption–based health impact
	Range (%)	Range (%)	Range (%)
Indonesia	64 – 142	64 – 142	64 – 138
Malaysia	65 – 171	65 – 155	59 – 159
The Philippines	65 – 154	64 – 151	63 – 148
Singapore	74 – 173	60 – 157	45 – 160
Thailand	60 – 144	57 – 137	56 – 136
China	64 – 136	59 – 133	61 – 132
Taiwan	44 – 159	49 – 158	43 – 160
South Korea	39 – 101	47 – 115	48 – 117
Japan	74 – 162	64 – 158	61 – 161

Figure 1

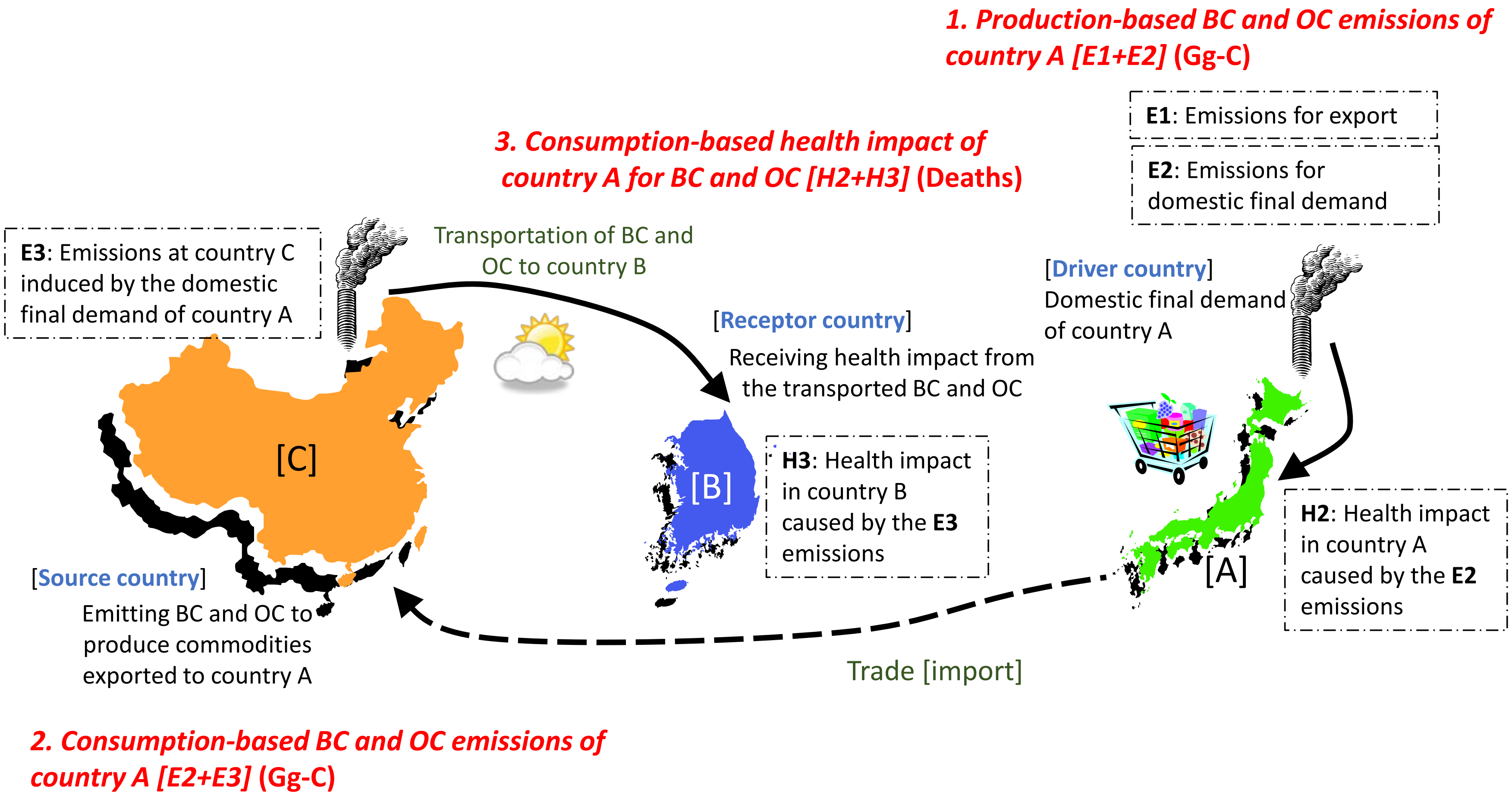

1. Production-based BC and OC emissions of country A [E1+E2] (Gg-C)
E1: Emissions for export
E2: Emissions for domestic final demand
3. Consumption-based health impact of country A for BC and OC [H2+H3] (Deaths)
E3: Emissions at country C induced by the domestic final demand of country A
Transportation of BC and OC to country B
[Driver country]
Domestic final demand of country A
[Receptor country]
Receiving health impact from the transported BC and OC
[C]
[B]
[A]
H3: Health impact in country B caused by the E3 emissions
H2: Health impact in country A caused by the E2 emissions
[Source country]
Emitting BC and OC to produce commodities exported to country A
Trade [import]
2. Consumption-based BC and OC emissions of country A [E2+E3] (Gg-C)

Figure 2

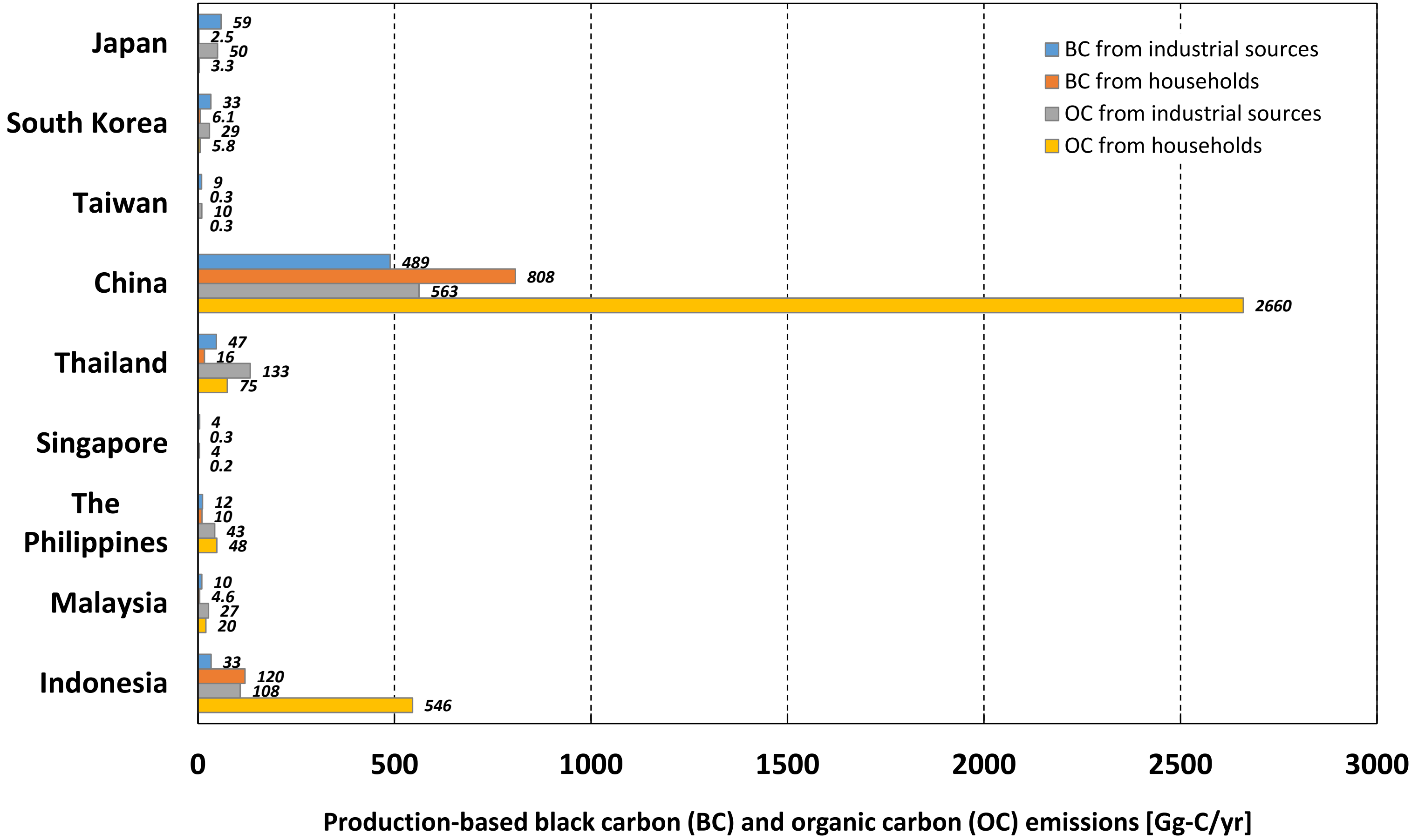

Japan
South Korea
Taiwan
China
Thailand
Singapore
The Philippines
Malaysia
Indonesia
59
2.5
50
3.3
33
6.1
29
5.8
9
0.3
10
0.3
489
808
563
2660
47
16
133
75
4
0.3
4
0.2
12
10
43
48
10
4.6
27
20
33
120
108
546
BC from industrial sources
BC from households
OC from industrial sources
OC from households
0
500
1000
1500
2000
2500
3000
Production-based black carbon (BC) and organic carbon (OC) emissions [Gg-C/yr]

Figure 3

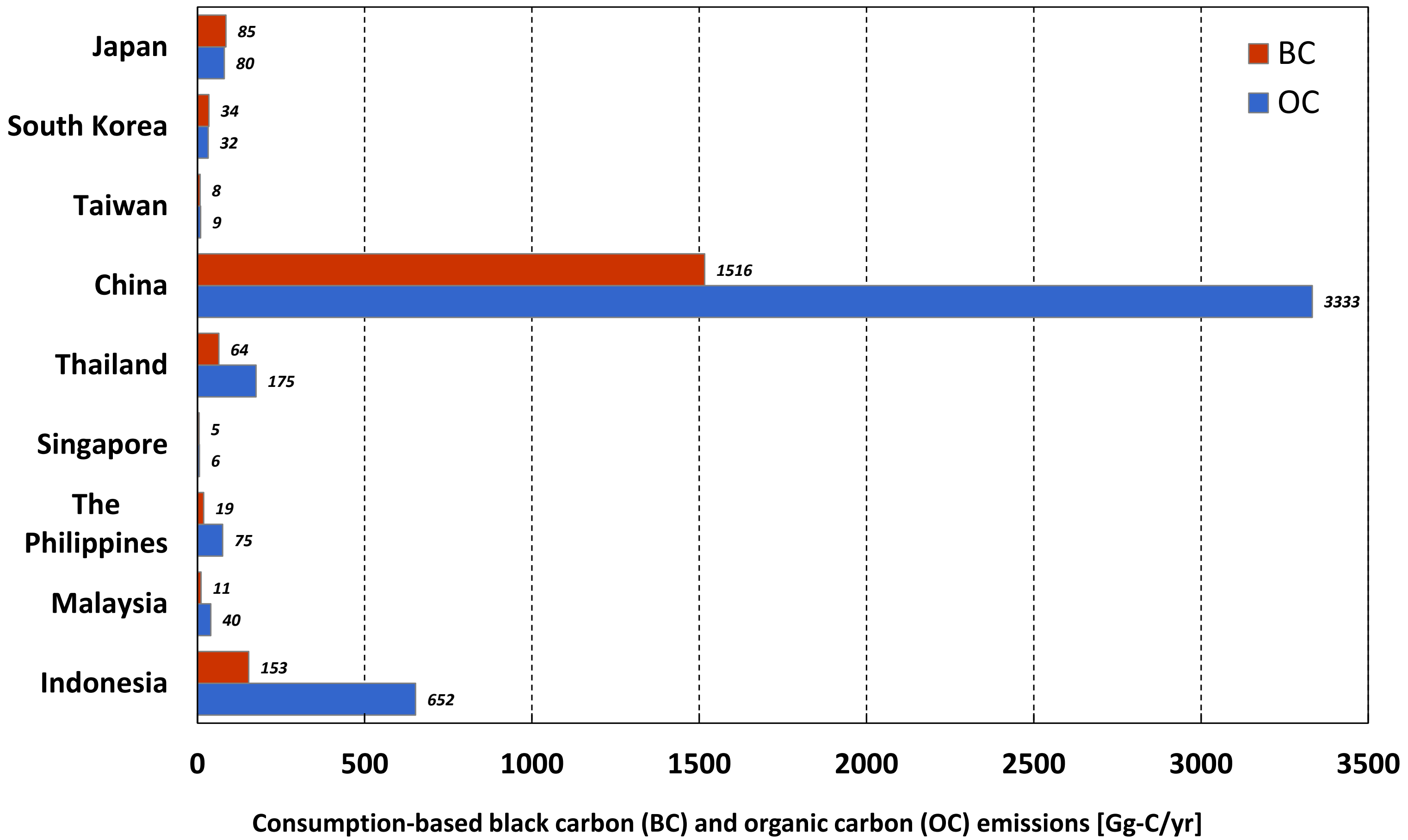
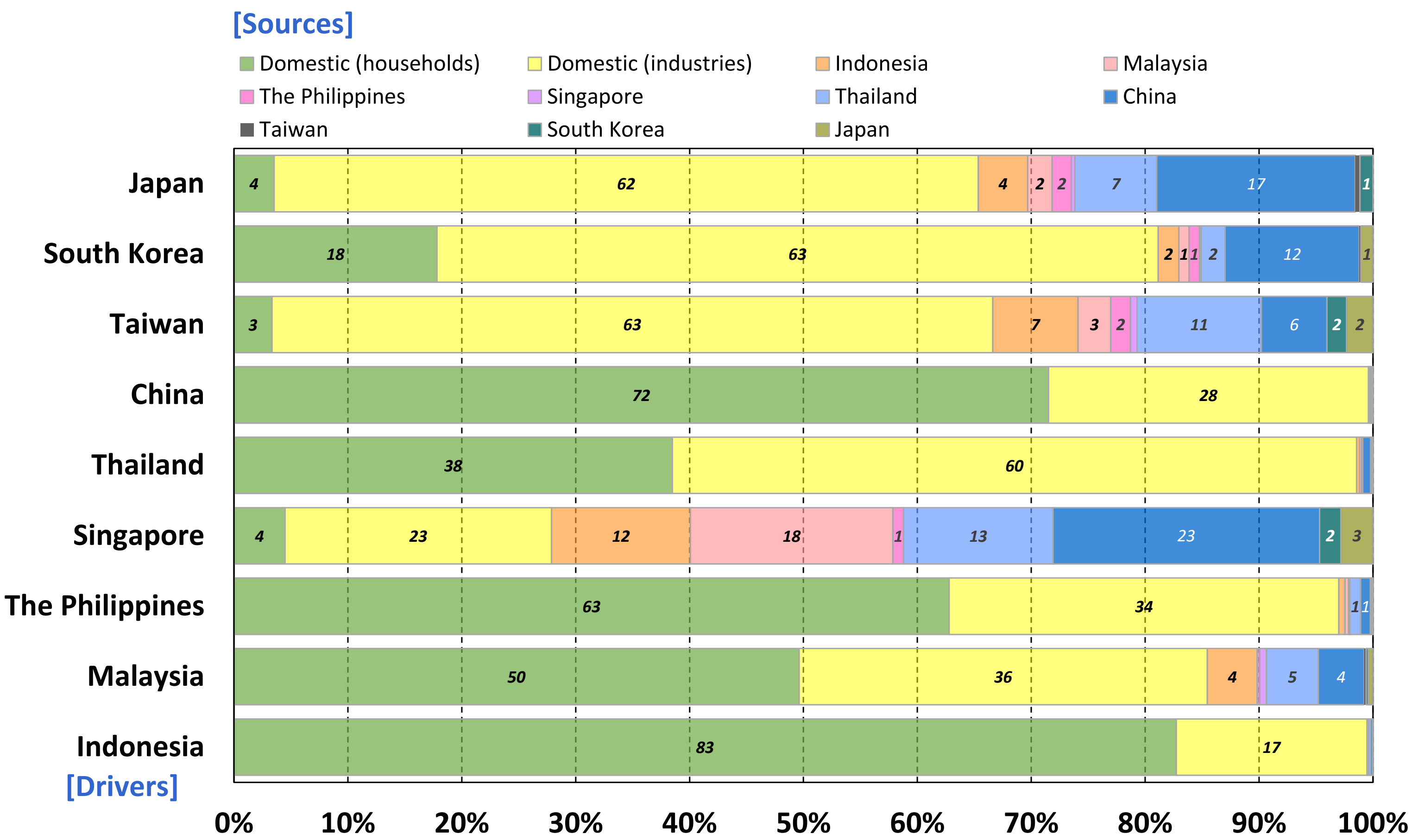

Japan
85
80
South Korea
34
32
Taiwan
8
9
China
1516
3333
Thailand
64
175
Singapore
5
6
The Philippines
19
75
Malaysia
11
40
Indonesia
153
652
BC
OC
0
500
1000
1500
2000
2500
3000
3500
Consumption-based black carbon (BC) and organic carbon (OC) emissions [Gg-C/yr]

Figure 4



Composition of countries and regions to which the domestic final demand of a country/region induced BC and OC emissions

Figure 5

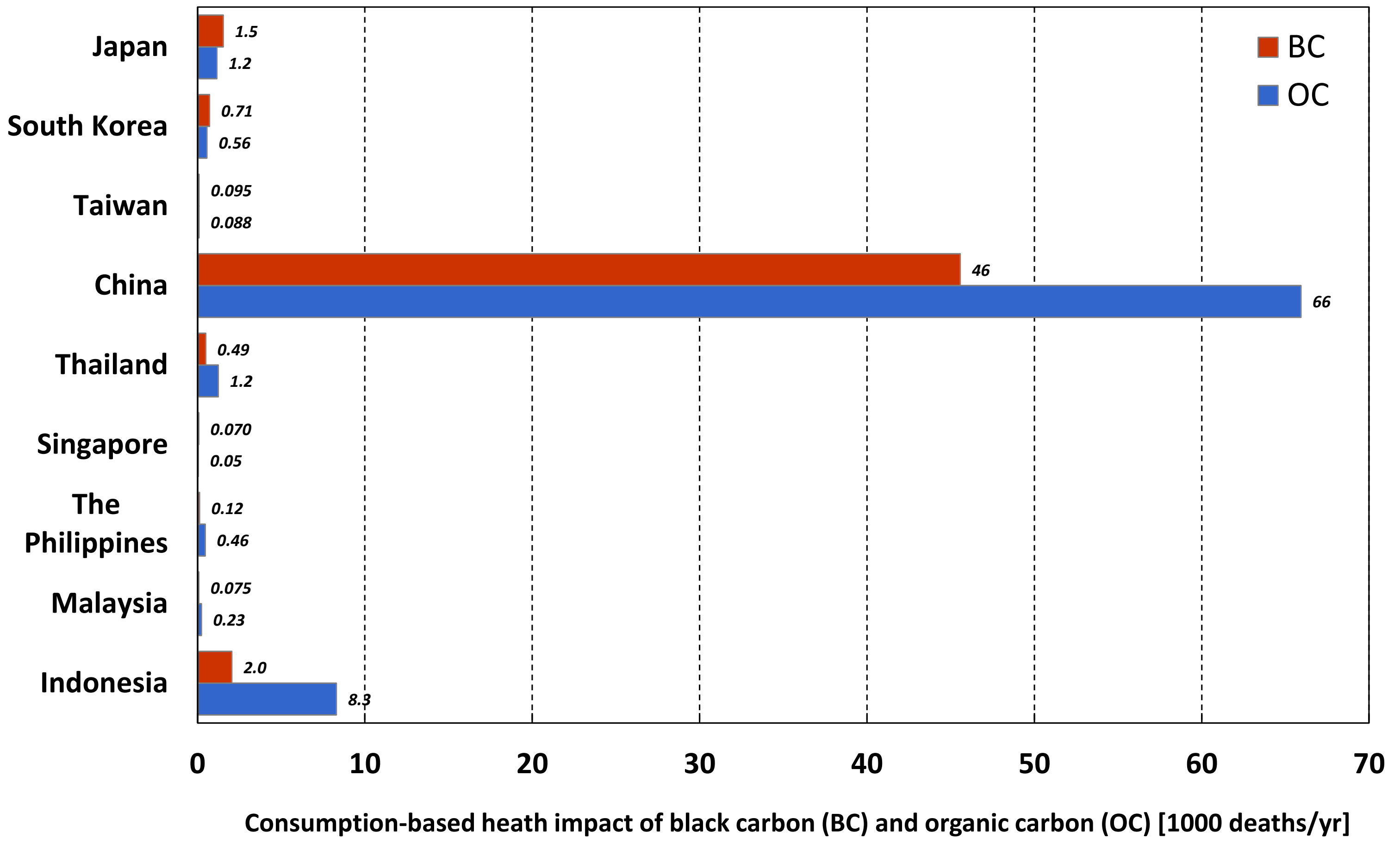
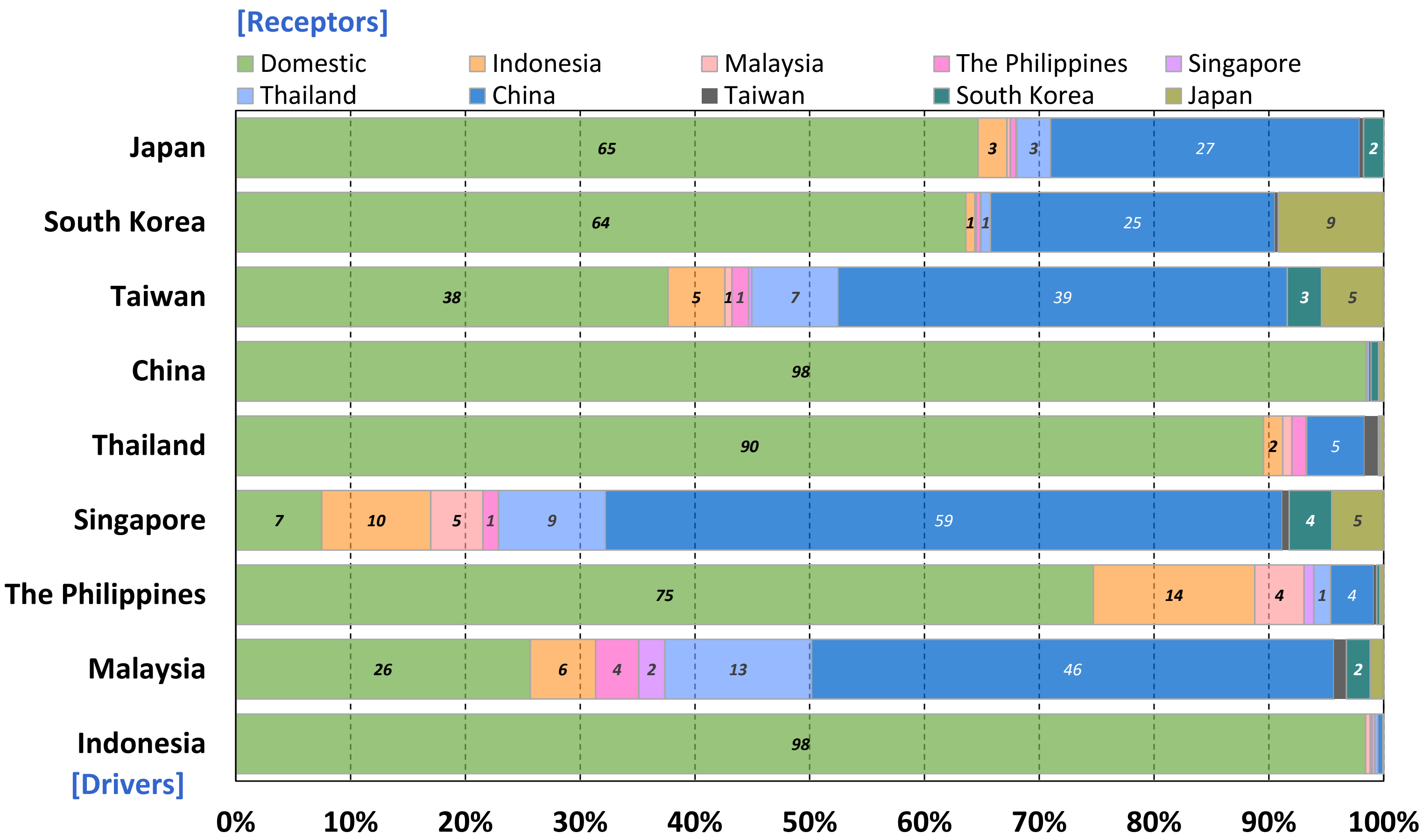
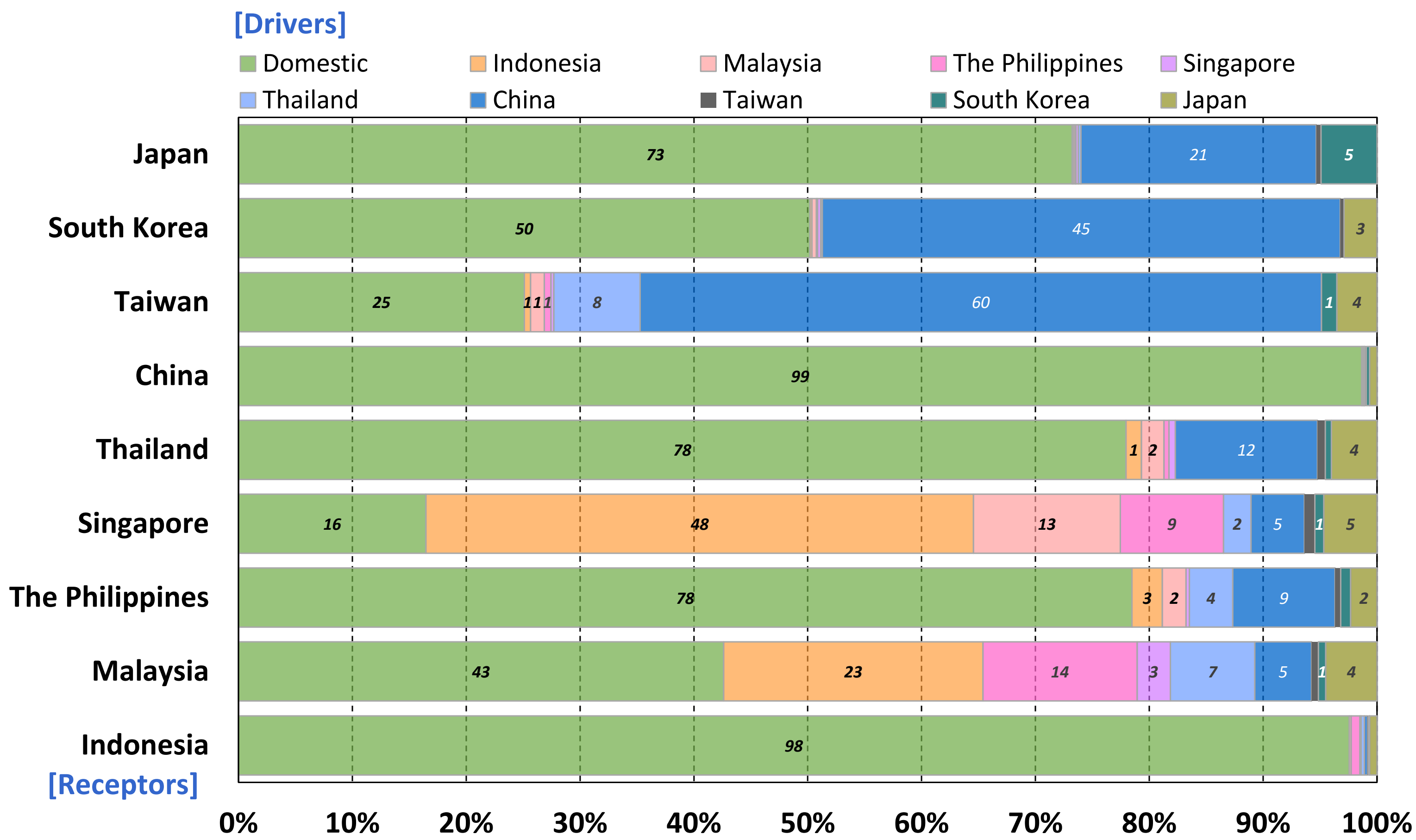

Japan
1.5
1.2
South Korea
0.71
0.56
Taiwan
0.095
0.088
China
46
66
Thailand
0.49
1.2
Singapore
0.070
0.05
The Philippines
0.12
0.46
Malaysia
0.075
0.23
Indonesia
2.0
8.3
BC
OC
0
10
20
30
40
50
60
70
Consumption-based heath impact of black carbon (BC) and organic carbon (OC) [1000 deaths/yr]

Figure 6



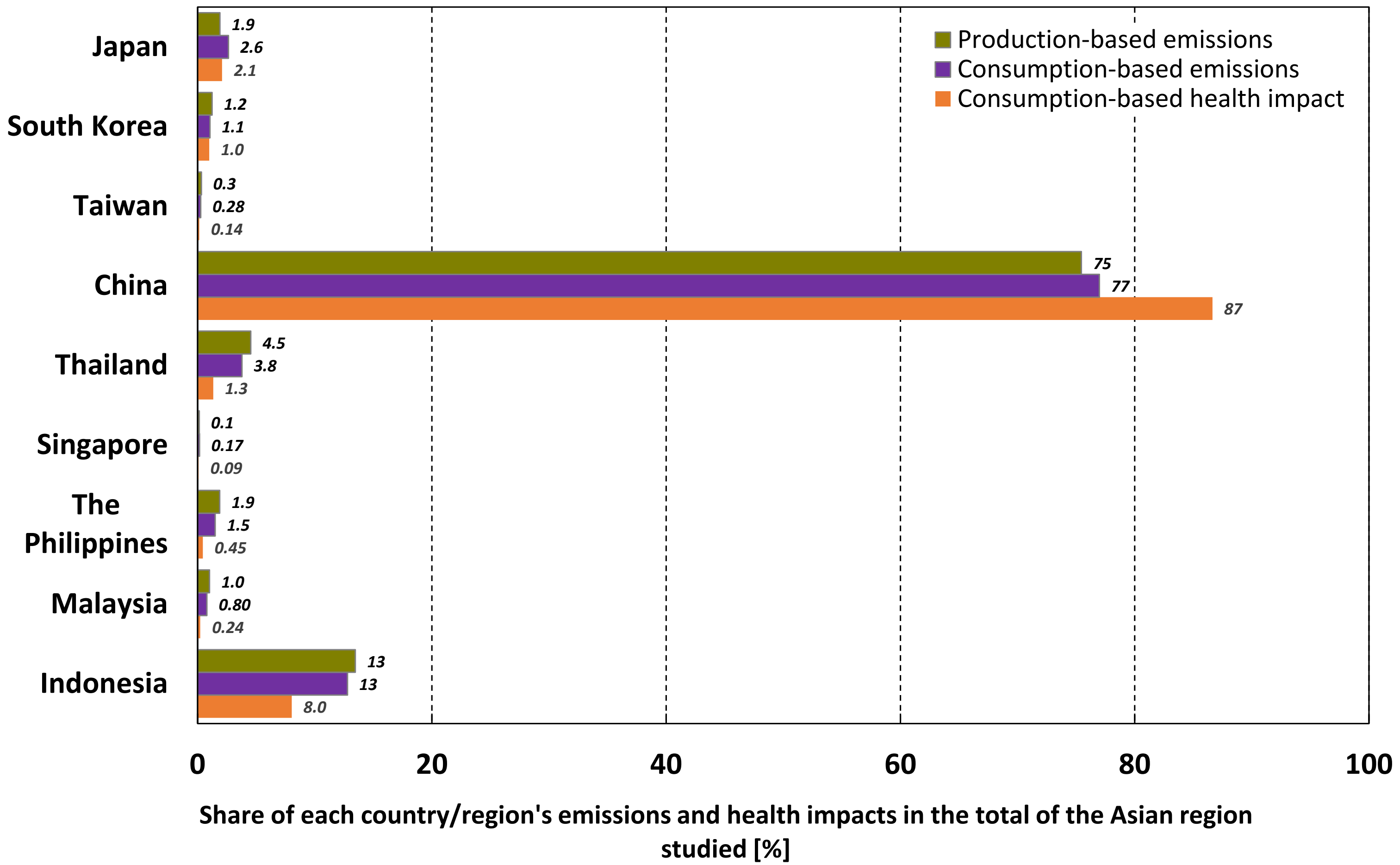
Composition of countries and regions to which the domestic final demand of a country/region induced a health impact associated with BC and OC emissions

Figure 7



Composition of health impact of BC and OC in each country/region by the countries and regions of which the domestic final demand induces the health impact

Figure 8


Japan
1.9
2.6
2.1
South Korea
1.2
1.1
1.0
Taiwan
0.3
0.28
0.14
China
75
77
87
Thailand
4.5
3.8
1.3
Singapore
0.1
0.17
0.09
The Philippines
1.9
1.5
0.45
Malaysia
1.0
0.80
0.24
Indonesia
13
13
8.0
Production-based emissions
Consumption-based emissions
Consumption-based health impact
0
20
40
60
80
100
Share of each country/region's emissions and health impacts in the total of the Asian region studied [%]